Project Closeout Report

HORIZONTAL STOCHASTIC COOLING

at the
Collider-Accelerator Department
at
Brookhaven National Laboratory
Upton, NY

for the
U.S. Department of Energy
Office of Science
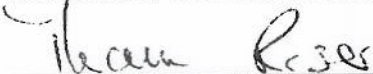Office of Nuclear Physics (SC – 26)

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September 2012

Project Closeout Report for Horizontal Stochastic Cooling
at the
Collider-Accelerator Department
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CONCURRENCES:

Date: 9.17.2012

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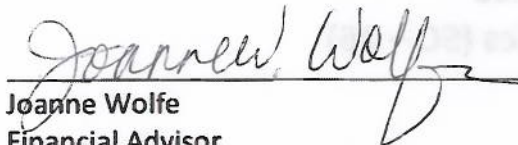Brookhaven National Laboratory

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1. Introduction

Extending the stochastic cooling system for RHIC to the horizontal planes has increased the integrated luminosity (collision rate) for physics production. The luminosity is a function of three main variables: ions per bunch, lattice beta function at the interaction point, and beam emittance. The first two variables had previously been optimized to their practical limit and the beam emittance, although optimized at the beginning of a production store was continuously degraded during the course of a store by intra-beam scattering (IBS), which caused the luminosity to fall to the point that the store is terminated, so that the collider needed be refilled with fresh beam. The drop off of instantaneous luminosity and the time it takes to refill and ramp the new beam made the integrated luminosity much less than the peak instantaneous luminosity. Stochastic cooling has counteracted the IBS by decreasing beam emittance thus keeping the luminosity high.

IBS at 100 GeV/nucleon in RHIC increased the emittance in all three-phase space planes, longitudinal, vertical, and horizontal. Implementation of stochastic cooling required separate cooling systems for each plane and each system is comprised of a beam pickup, signal processing electronics, and a high voltage broadband kicker. As these components couple to only one beam coordinate at a time the hardware of the cooling system needed to be replicated for each plane. We had previously implemented cooling systems for two of the three planes (longitudinal and vertical), and this ARRA funded project completed the full system by implementing horizontal cooling.

The technology of the equipment had been developed and tested in the previously completed systems. Special measures had been developed to satisfy the unique requirements for cooling bunched beam in a high-energy collider. To reach a useful cooling rate the system must operate at high frequency. Our longitudinal cooling covers 6 to 9 GHz bandwidth and the first transverse system uses 5 to 8 GHz. RF power for the kickers is the dominant hardware cost for these systems. The kickers have been optimized for the bunched-beam nature of the collider. They are comprised of narrowband cavities that generate high voltage with only a few watts of input power by accumulating energy from the amplifiers in the time interval between the bunches. The effective bandwidth of the system is 3 GHz even though the actual bandwidth of the narrowband kickers is much smaller. The kicker-amplifier package is a modular design. The specific dimensions of the microwave cavities of the kicker were tailored for orientation in the new plane, but the fabrication technique and the installation equipment used the previous design.

One of the main problems for stochastic cooling of bunched beam was the issue of coherent lines in the Schottky spectrum. This was studied extensively with ion beams cooled in RHIC, compared to protons that are stored in other colliders. The studies led to the development of signal processing electronics that cope with the coherent lines encountered in cooling ions. The electronics that had proven effective in the first cooling system used in the longitudinal plane was repeated in the horizontal plane.

There are strong interactions in the beam between the different phase space planes. Firstly, IBS couples the cooling rate between the planes because reducing the emittance in one plane will increase the IBS growth rate in the other. Secondly, betatron coupling will tend to

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transfer emittance from one transverse plane to the other. Cooling rates must be optimized to strike a balance between emittances and IBS growth rates. This aspect of the design had been studied via simulations but complete simulation was only practical if an accurate scaling formulation was applied to keep the number of macroparticles manageable. The cooling time is proportional to the number of particles in the beam. One can scale down the number of particles for the simulation and scale up the resulting cooling time. IBS kicks are scaled to the local particle density and applied randomly to each turn of the macroparticles. The approach had been benchmarked by comparing predictions with measured results from longitudinally cooled gold beam. The simulations showed that adding cooling in both transverse planes, and balancing the cooling rate between longitudinal and transverse all add to the integrated luminosity. An average luminosity of $>3 \times 10^{27}$ cm^{-2}s^{-1} in a 5 hour store was expected.

2. Management

The Federal Program Manager for the Stochastic Cooling project is James Sowinski and the Contractor Project Manager at BNL is Alex Zaltsman.

3. Project Baseline

3.1. Technical Scope and Deliverables Baseline

The scope of this project was to engineer, procure and install a horizontal Stochastic Cooler and associated equipment in both the RHIC Blue and Yellow rings. Each ring contains one pickup plus 2 vacuum vessels with 8 cavities per vessel. The major procurements include amplifiers, electronics and vacuum vessel assemblies.
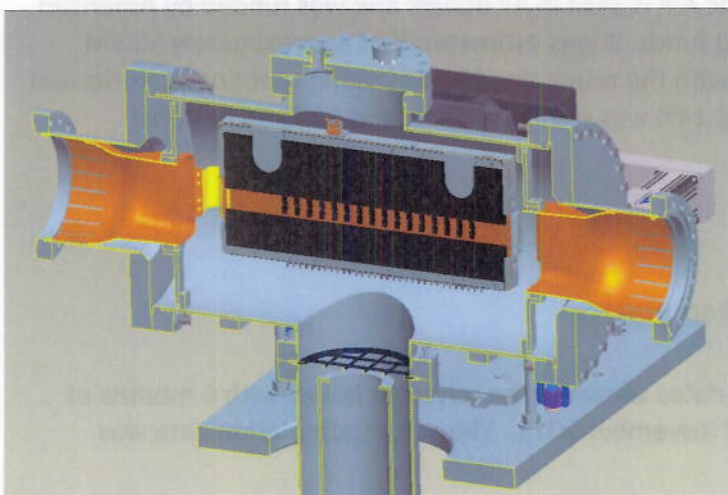

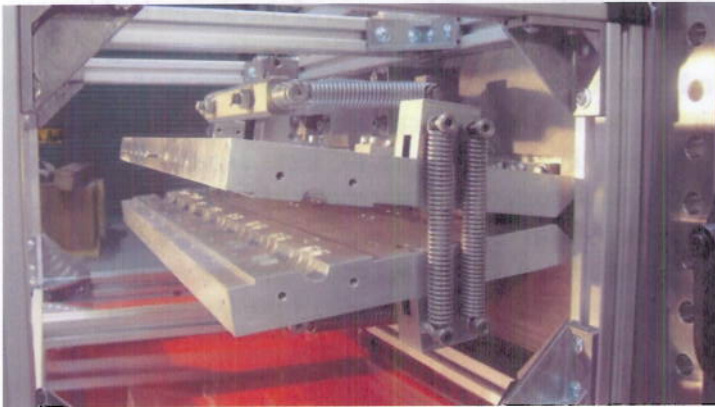Figure 1: Horizontal stochastic cooling pick-up design.

Figure 2: Prototype for a horizontal stochastic cooling kicker.

Successful project completion is defined as: All components are installed in the RHIC ring and the following critical parameters were verified: (1) All cavities are within the 3dB bandwidth of their operating frequency before vacuum vessel closure. (2) The power amplifiers have the specified gain (46dB) and power (46dBm).

With these criteria, the project had already been successfully completed when the RHIC Run-12 started in January 2012.
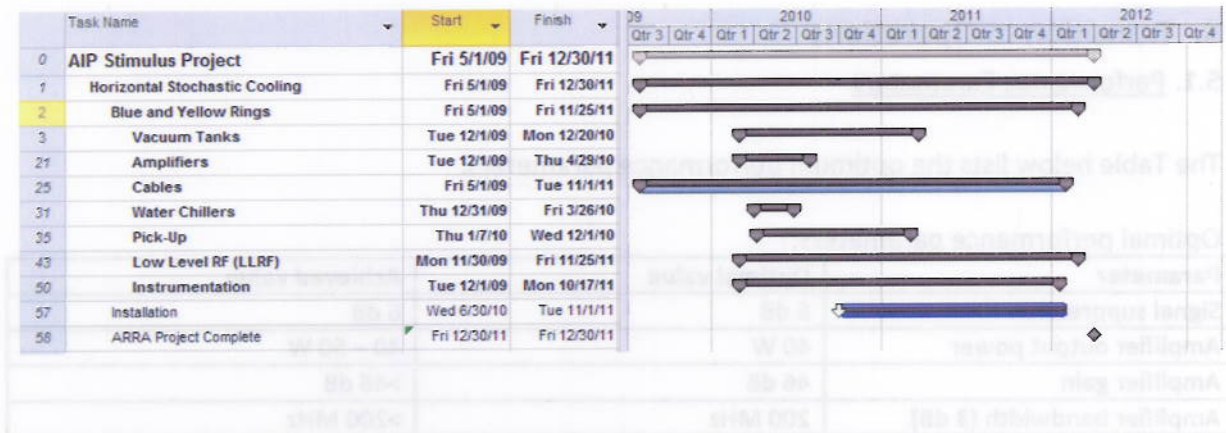
3.2. Cost Baseline

The Total Project Cost for the Stochastic AIP is $4M in AY dollars and was funded by American Recovery and Reinvestment Act (ARRA) funds. It was estimated that approximately $0.5M (~15%) will have been spent on labor, with the remaining $3.5M (~85%) spent on material and equipment. The actual costs show that 14% was spent on labor, and 86%) on material.

There was no project contingency.

3.3. Schedule Baseline and Milestone Performance

The Project worked to the Early Finish dates shown in the schedule below with 6 months of float to the Project completion date of November 2011. The actual completion date was December 2011.

	Task Name	Start	Finish	'09	2010	2011	2012
0	AIP Stimulus Project	Fri 5/1/09	Fri 12/30/11				
1	Horizontal Stochastic Cooling	Fri 5/1/09	Fri 12/30/11				
2	Blue and Yellow Rings	Fri 5/1/09	Fri 11/25/11				
3	Vacuum Tanks	Tue 12/1/09	Mon 12/20/10				
21	Amplifiers	Tue 12/1/09	Thu 4/29/10				
25	Cables	Fri 5/1/09	Tue 11/1/11				
31	Water Chillers	Thu 12/31/09	Fri 3/26/10				
35	Pick-Up	Thu 1/7/10	Wed 12/1/10				
43	Low Level RF (LLRF)	Mon 11/30/09	Fri 11/25/11				
50	Instrumentation	Tue 12/1/09	Mon 10/17/11				
57	Installation	Wed 6/30/10	Tue 11/1/11				
58	ARRA Project Complete	Fri 12/30/11	Fri 12/30/11				

The chart below shows the project milestones, some of which were reportable for ARRA funding purposes.

Stochastic Cooling Plane Milestones	planned mo/yr	actual mo/yr	ARRA milestones
Obligate Funding to BNL	Jun-09	Jun-09A	x
Start Design	Jun-09	Jun-09A	x
Begin Purchasing	Jul-09	Aug-09A	x
Start Fabrication	May-10	Feb-10A	x
Water Chillers available for Installation	May-10	Apr-10A	-
50% of cavities tested and sent for plating	Sep-10	Jun-10A	-
Begin Construction	Nov-10	Jul-10A	x
Kicker tanks received from manufacturer	1QFY11	Nov-10A	-
LLRF installation 50% complete	2QFY11	Mar-11A	-
Start Assembly of Cavity and Tanks	Mar-11	Nov-10A	x
Pick up tanks assembled and tested	3QFY11	Jun-11A	-
LLRF installation complete	3QFY11	Jun-11A	-
Cables 50% complete	3QFY11	Jun-11A	-
Begin Installation	Aug-11	Jul-11A	x
Cables 100% complete	4QFY11	Nov-11A	-
Accelerator Systems Safety Review	1QFY12	Nov-11A	-
Radiation Safety Review	1QFY12	Nov-11A	-
Complete installation	1QFY12	Nov-11A	-
Start Commissioning	Nov-11	Nov-11A	x
Planned Early Finish Date	2QFY12	Dec-11A	-
Project Complete	May-12	Dec-11A	x

3.4. Funding

Funding of $3.6M was received in May 2009, and the remaining $0.4M in July 2009.

4. Closeout Status

By August 30, 2012 all commitments had been resolved.

5. Transition to Operations

5.1. Performance Parameters

The Table below lists the optimum performance parameters.

Optimal performance parameters:

Parameter	Optimal value	Achieved value
Signal suppression	6 dB	6 dB
Amplifier output power	40 W	40 – 50 W
Amplifier gain	46 dB	>46 dB
Amplifier bandwidth (3 dB)	200 MHz	>200 MHz

One horizontal pickup tank was installed in RHIC prior to the FY2011 run. During this run, the performance of the pickup with beam was measured to verify adequate signal-to-noise ratio. During the FY2012 polarized proton run, the motion of the pickups and kickers was tested to verify that the aperture in the closed position did not cause beam losses. Commissioning of the system proceeded rapidly during FY2012 uranium run. The propagation delay of the signal from the pickup to the kicker was measured, and after addition of an appropriate fiber optic delay coil, verified to be correct. At this point, the beam transfer functions were measured and signal suppression was observed. Signal suppression is the reduction of the power in the betatron sidebands of the Schottky signal due to the cooling system. In order to observe signal suppression, the cooling system must be operating correctly, so this is considered a final test of the complete system. The optimal cooling rate is achieved with about 6 dB of signal suppression. This value was achieved in the horizontal cooling systems during routine operation in both the FY2012 uranium and copper-gold runs.
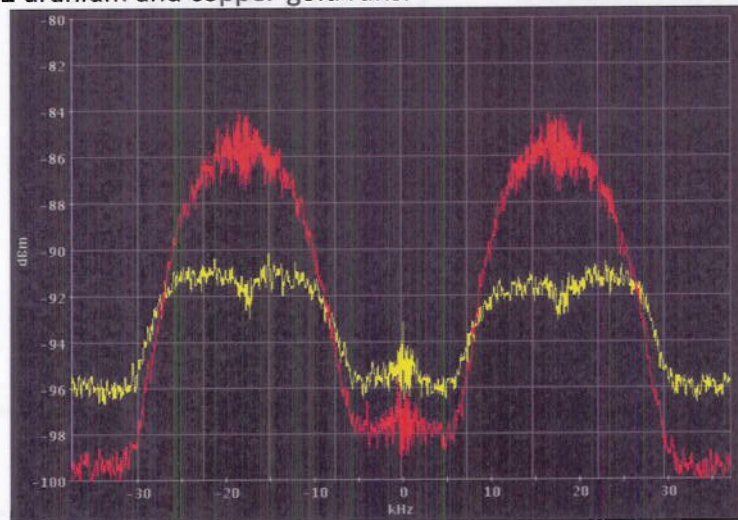

Figure 3: Schottky spectra at 5.8 GHz illustrating 6 dB (optimal) signal suppression. The red trace is the Schottky spectrum measured with the cooling off, and the yellow trace is with the cooling on.

The commissioning required the full-time commitment of the system physicist and the system engineer during the RHIC Run-12, with support from the RF, instrumentation, controls and vacuum groups as needed.

5.2. Schedule

The commissioning milestones and Gantt chart are presented below. All milestones were met by the end of RHIC Run-12 in June 2012.

Stochastic Cooling Commissioning Milestones	planned mo/yr	actual mo/yr
Resonant frequencies verified after bake-out	Jan-12	Dec-11
Microwave amplifies verified in tunnel	Jan-12	Dec-11
Aperture check for pickup and kicker (open and close)	Jun-12	Jun-12
Signal suppression demonstrated	Jul-12	Jun-12

	Task Name	Start	Finish	2012 Nov Dec Jan Feb Mar Apr May Jun Jul
1	Verification of Cavity Frequencies	Thu 12/1/11	Fri 12/30/11	
2	Verification of microwave amplifiers	Thu 12/1/11	Fri 12/30/11	
3	Aperture test of pickup and kicker	Wed 2/1/12	Sat 6/30/12	
4	Signal supression demonstrated	Tue 5/15/12	Sat 6/30/12	

5.3. Impact on Collider Performance

The amount of data created for the STAR and PHENIX experiments in a three-week exploratory U+U run was increased five-fold by 3D stochastic cooling. The cooling is so strong that the emittance is decreased by a factor of 5 after an hour of storage time (Figure 4), and the peak luminosity or collision rate is three times higher than the initial one. This has never been achieved before in a hadron collider. With a re-optimized lattice and stochastic cooling, uranium ions were only lost through U-U collisions, which offers a method of determining to the total U-U cross section (very preliminary data in Figure 5).

The effect of the new horizontal planes on the luminosity in U-U stores can be seen in Figure 6, an increase of 20-25% over the case of longitudinal and vertical cooling only. Figure 7 shows the expected increase in Au-Au operation (not done in 2012), which also includes a further increase in the bunch intensity.

Finally, Figure 8 shows a Cu-Au store. In asymmetric operation the cooling rates have to be adjusted so that the beam sizes of both beams remain equal (otherwise the larger beam will shed particles). Once this was accomplished, the optimum store lengths became as long as 14 h.
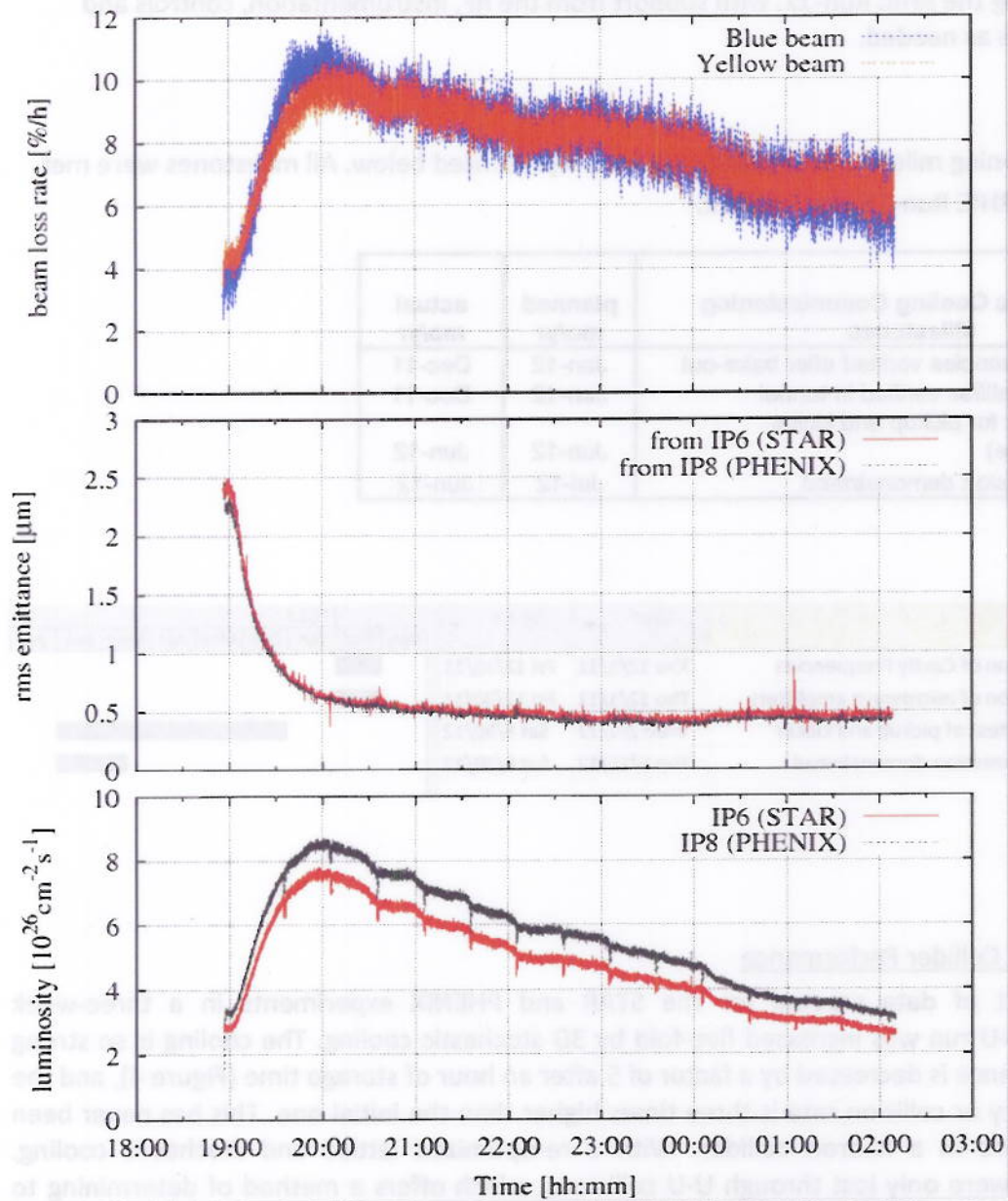
Figure 4: Beam loss rate (top), emittances (middle) and luminosity (bottom) of a uranium store. The emittance (middle) is reduced by a factor of 5, and the luminosity increases by a factor of 3 from the initial value. The absolute beam loss rate is proportional to the luminosity and due to burn-off.
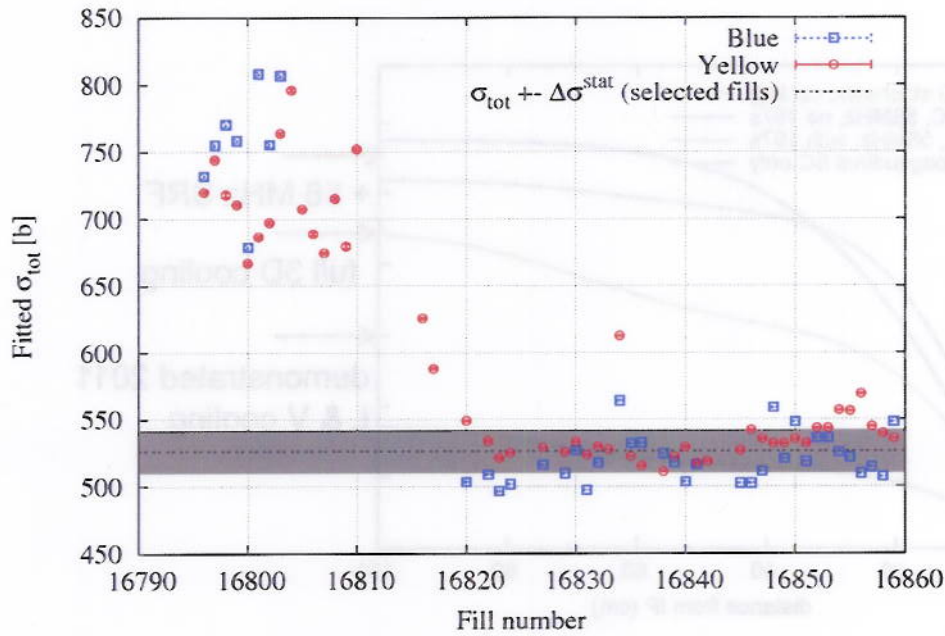
Figure 5: Fitted total U-U cross section at √s_NN = 192.8 GeV. The burn-off limit was (likely) reached with full 3D cooling (fill number 16820 and higher), and the total cross section can be extracted from a linear fit of absolute loss rate vs. luminosity (the statistical standard errors of the linear fit are smaller than the symbol sizes). [First pass of data analysis only, very preliminary, needs full discussion of all systematic errors.]
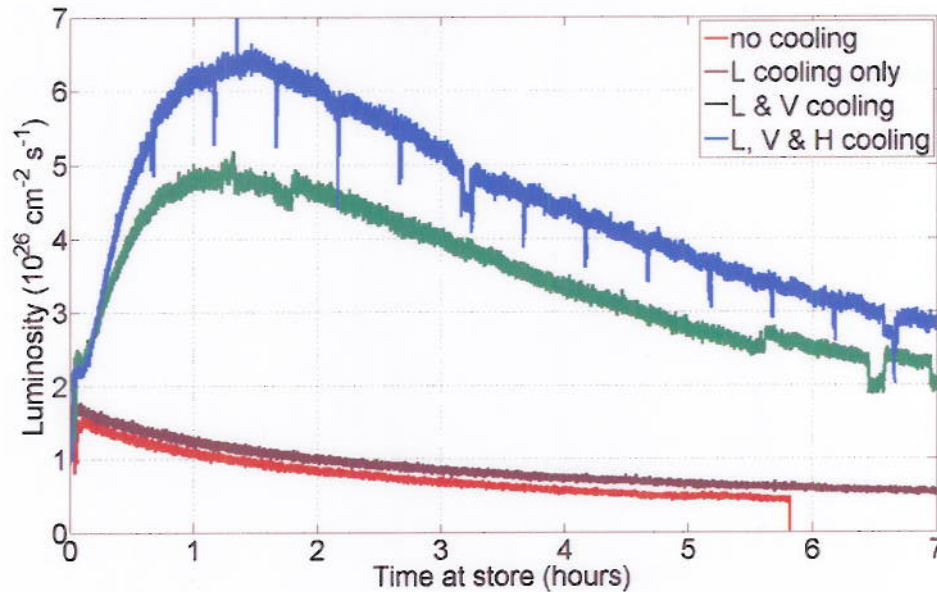

Figure 6: Luminosity (collision rate) for UU stores without cooling; with longitudinal cooling only, with longitudinal and vertical cooling; and with cooling in all planes.
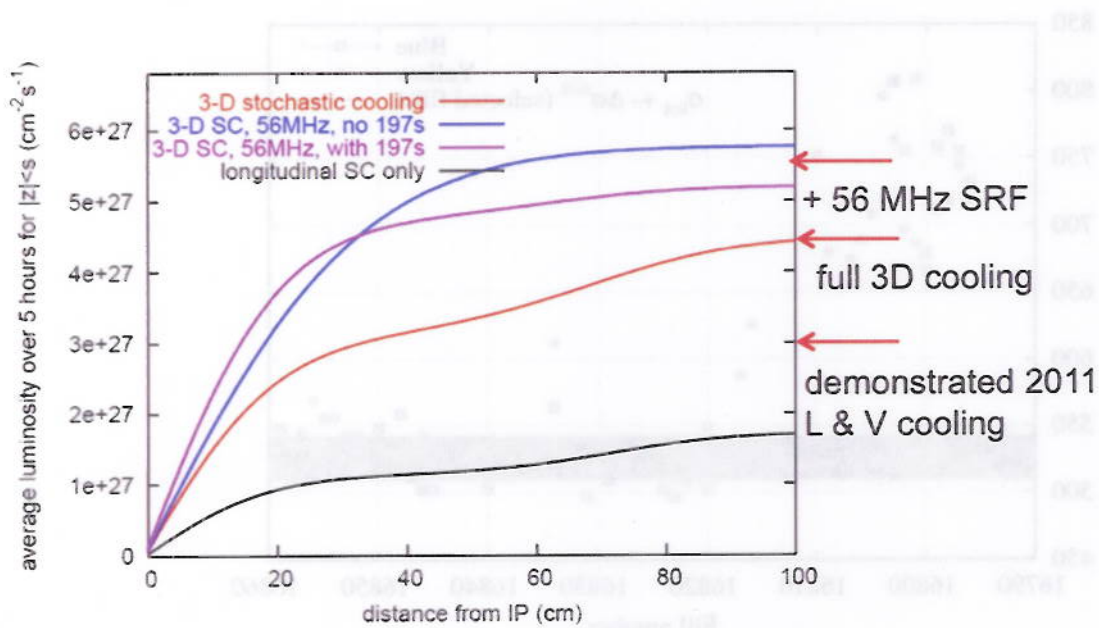
Figure 7: Calculated average store luminosity (M. Blaskiewicz) as a function of vertex size for Au-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Arrows indicate the demonstrated performance in 2011 with longitudinal and vertical cooling, and the expected Au-Au performance with cooling in all three planes. Indicated also is the further luminosity increase with the 56 MHz SRF system under construction.
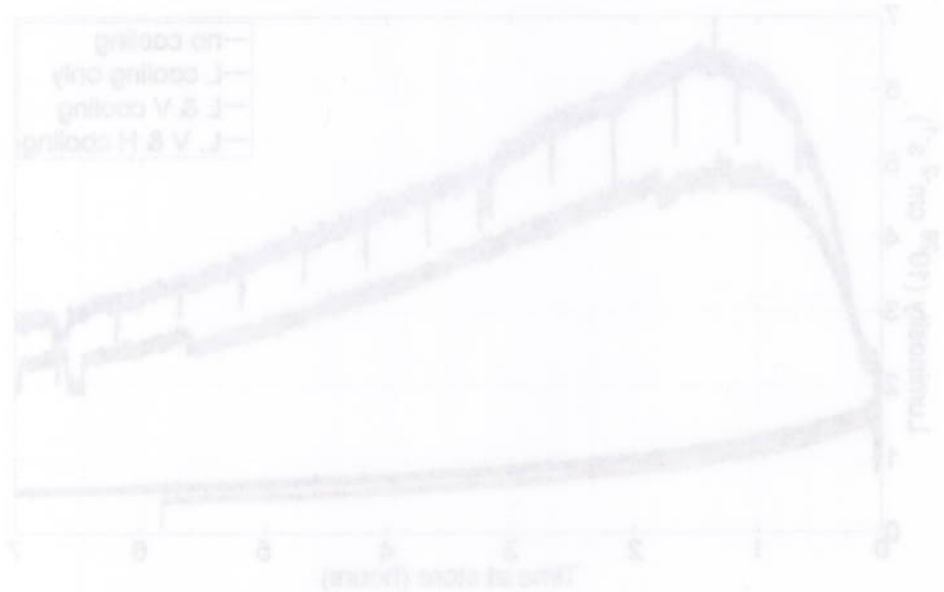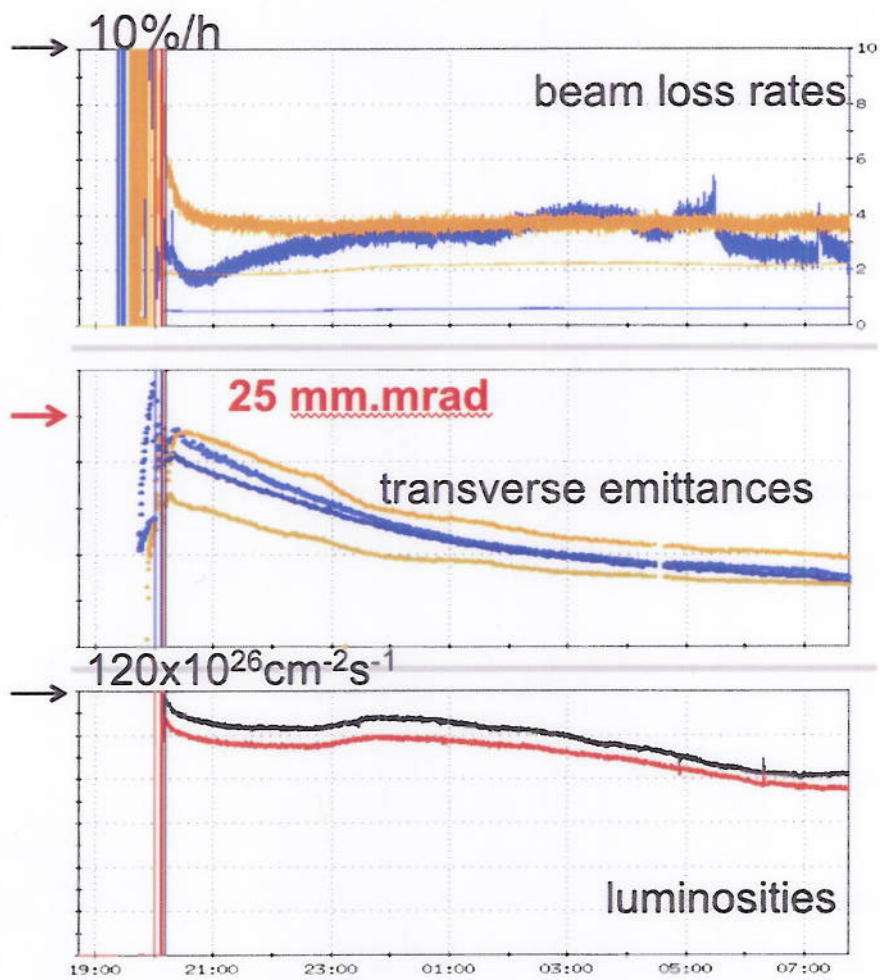
Figure 8: Beam loss rate (top), transverse rms emittances (middle) and luminosities (bottom) for a Cu-Au store in RHIC in 2011.

Figure 8: Beam loss rate (top), transverse rms emittances (middle) and luminosities (bottom) for a Cu-Au store in RHIC in 2011.